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Journal:	*International Journal of Science Education*
Manuscript ID:	TSED-2006-0264.R1
Manuscript Type:	Research Paper
Keywords:	conceptual development, misconception, secondary school, alternative conception, chemistry education
Keywords (user):	

Upper secondary French students, chemical transformations and the "register of models": a cross-sectional study

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UPPER SECONDARY FRENCH STUDENTS, CHEMICAL TRANSFORMATIONS AND THE REGISTER OF MODELS: A CROSS-SECTIONAL STUDY

Abstract

The purpose of this study is to identify how upper secondary school French students (grade 10 to 12) interpret chemical transformation with regards to the changes within molecules and atoms and in terms of intramolecular and/or intermolecular bond breaking. In order to identify and describe the students' assimilated knowledge, four questions were asked to 930 students using a written questionnaire submitted a long time after the related teaching took place. There is much research into student learning in the concept areas discussed here (atoms and molecules, chemical change, chemical bonding) as reviewed in the paper. The present study presents data from an educational system where limited work has been reported in the international literature. The French system has its own unique curriculum, and is taught in the national language (where much of the existing research has concerned learning in Anglophile systems). The research reported here found that French secondary students experienced many similar difficulties in understanding these key scientific concepts to those that have been reported elsewhere, showing the cross-cultural nature of the key educational issues. For example, many have difficulties in understanding the changes undergone by atoms and molecules in the course of a chemical reaction; many are not able to justify explicitly the breaking of inter-molecular bonds and to interpret the breaking of intra-molecular bonds in terms of reorganization of atoms, the target level of understanding in the curriculum from the end of grade 9. However, it is also suggested that some of the specific characteristics identified here are linked to the ordering and language used in the French curriculum, and such cultural idiosyncrasies may offer useful insights into both problematic and valuable aspects of science pedagogy.

Introduction

To differentiate a chemical transformation (i.e. a 'chemical change') from a change of state (i.e. a 'physical change') requires the mastering of the different concepts used in science to understand and model the process (such as chemical compound, molecule, atom, ions, and of particular significance in this study, "element", etc.), including an appreciation of the distinction between intra- and intermolecular bonding; and also how these concepts are linked in terms of the relationship between the macroscopic level of observation and the sub-microscopic 'molecular' level that is the basis of much chemical explanation. As Hesse and Anderson (1992) observe, the difference between chemical and physical transformations *"is far more complex than many teachers and textbook authors usually think"* and they add that the *"learning of chemical transformation requires complex modifications in many students' conceptual ecology"*. Therefore, it is not surprising that many studies should underline students' difficulties in differentiating between the two types of transformation (Meheut, 1989; Brosnan, 1990; Sanmarti et al., 1995).

Analysis of previous research

A great deal of research has been undertaken that underlines the problems encountered by students in understanding matter transformation. In the "register of models" (a term to be discussed below) it has been shown that students find it difficult to master the key concepts involved: atom, molecule, ion, chemical bonds, etc. (Butts & Smith, 1987; Peterson & Treagust, 1989; Griffiths & Preston, 1992; Keig & Rubba, 1993; Taber, 1994, 1995, 1997, 1999, 2000; Garnett et al., 1995; Harrison & Treagust, 1996 ; Taber & Watts, 1996; Boo, 1998; Johnson, 1998; Robinson, 1998; Tsai, 1998; Tan & Treagust, 1999, Barker & Millar, 2000; Coll & Treagust, 2001, 2002; Coll & Taylor, 2002)

The language used by those inducted into chemistry (and so instinctively and habitually thinking about chemical structures and changes in terms of 'molecular level' models) may also be a confounding factor. Chemists commonly use the word 'atom' both for atoms themselves, and loosely for the parts of molecules that comprise atomic cores (nucleus + core electrons) plus associated electrons. Talk of atoms being conserved during chemical change is *literally* an oxymoron, but implies that the same *atomic cores* are part of the molecular, ionic etc. structures in reactants and products. This seldom causes problems when professional chemists talk, as this meaning of 'atom' is clear from the context.

As the literature we discuss here suggests, students do not fully share this framework for making sense of the subject. As a result, they find it difficult to imagine how atoms reorganise during a chemical transformation (Ahtee & Varjola, 1998; Laugier & Dumon, 2000), and Boo and Watson (2001) show that students (16-18 years old) have great difficulty in appropriating the idea that if 'atoms' are intrinsically conserved, the reorganization of their electrons leads to different properties. So, for some students, a chemical reaction is more a process of "modification" that leads to the juxtaposition (addition, gluing) of reactants than a transformation during which chemical bonds break and reform (Ben Zvi et al., 1987, 1988; de Vos & Verdonk, 1987; Andersson, 1990; Caamano Ros, 1993; Sanmarti et al., 1995). This is why some students believe that molecules are conserved during a chemical reaction (Andersson, 1990). Moreover, most students (92% in Solsona et al., 2003) cannot relate the macroscopic and sub-microscopic levels. (Stavridou & Solomonidou, 1989; Johnstone, 1991; Harrison & Treagust, 2000; Laugier & Dumon, 2000; Taber, 2001b; Dori & Hameiri, 2003).

Studies on the understanding of inter- and intra-molecular bonds (Cros et al., 1986; Kiokaev, 1989; Peterson & Treagust, 1989) have shown that students cannot differentiate between these two sorts of "bonds" easily. Besides, for some students, there is no bond between molecules in the condensed phases of substances that comprise of simple molecules (Taber, 1993). For the dissolution mechanism, Boo and Watson (2001) report that a significant proportion of students cannot understand the role played by the water. For them, as the water was present at the beginning of the reaction and it is still present at the end, it therefore has no part in the dissolution.

The curriculum context

When leaving lower secondary level (i.e. on completing grade 9), a French student is expected to know that the pure simple molecular compound is made of a great many identical molecules. These molecules are the same in the three states of matter: gaseous (dispersed and disordered), liquid (compact and disordered) and solid (compact and ordered). According to the target knowledge set out in the curriculum, the molecules are considered to be formed from a combination of different atoms. During a chemical reaction (symbolised by a reaction equation) the atoms are considered to be conserved in nature and in number. They are reorganised within the formulae that represent the reactants and the products. The teaching model of atom is the neutral atom model: a positively charged nucleus and negatively charged electrons that move (described in French schools as 'revolving') around the nucleus (labelled the "electron suite"). The nucleus of the atom contains as many positively charged units as there are electrons around it. Of course, as pointed out above, if this is 'the' meaning of atom, then it is problematic to talk of atoms in molecules, or atoms conserved during reaction. The mass conservation principle of Lavoisier is often illustrated by French teachers with the maxim "*nothing is lost, nothing is created, everything changes*" popularized by Dumas in 1836 ("Leçons sur la philosophie chimique", p. 133).

In upper secondary school, at grade 10 (i.e. 15-16 years), the basic atomic teaching model is the same but the nuclear sub-atomic particles are introduced (protons and neutrons). The electron suite (or 'revolving' electrons) contains Z electrons distributed in shells (K, L, M,…). At this stage the concept of "*element*" is introduced as follows: an element is characterized by its symbol X and its atomic number Z (i.e.; the number of protons) (symbolized by $_{Z}X$). The different isotopes of an atom correspond to the same element.

The term 'element', as used in France, refers to the common component of the elementary substance (e.g. Cl_2) *and* any of its compounds (NaCl, CH_3Cl, etc.). It is the element of Mendeleyev, which indicates: *"…the material part which is common to the simple body and all its compounds.[…] The word element calls the idea of atom"* (Mendeleyev, 1879); not the usage of Lavoisier's (the element simple compound). A "chemical transformation" is defined as a change of the state of the chemical system (T, P, chemical composition) from the initial to the final state: it is the observed phenomena at macroscopic level. The change of chemical composition is modelled at macroscopic level by a "chemical reaction" (reactants → products) and symbolized by a reaction equation. At the atomic or molecular level, the writing of the equation of the chemical reaction shows the conservation of the chemical "elements" and the reorganisation of atoms; some bonds are broken, others are made and the external electronic structure of some atoms is modified. In this way, the nature of atoms change but the elements are conserved. The association of atoms within a molecule can be represented by a Lewis representation. At grade 11, inter-molecular interactions within condensed phases, in substances comprised of simple molecules, appear in the curriculum, and so does the role played by the water during the dissolution of covalent and ionic compounds. In an ionic lattice, the binding results from Coulombic interactions between ions. The energies of chemical transformation and changing of state are respectively related to the energies of binding of the associations of atoms in isolated gas molecules (covalent or intramolecular bonds) and assembling molecules in molecular liquids or solids (intermolecular interactions).

Theoretical background

For Martinand (1995), the processes of modeling are to ply between two different domains: that of the "empirical referent" (which speaks about the concepts, the models or the theories), constituted by objects from reality and phenomena, but also by practices on these objects and these phenomena (labelled *"empirical register"*), and that of the theories and models which provide tools that allow for the building of a representation of objects and observed phenomena (labelled *"register of the models"*). The "register of models" is consequently all representations available to a student to represent, explain or predict phenomena in real world, i.e. with regard to our study, the models concerning matter and this transformation teaches at one given grade level. For example, at grade 10, the register of models would include molecule, atoms and their reorganization, electronic structure, covalent bond, element, etc (See curriculum context for further details). A student elaborates his or her scientific knowledge by linking between registers. The problem in chemistry is that a world of theories and models is essentially constituted on conjectured entities that are on the molecular scale, symbolized in terms of chemical formula. They can not be learnt in terms of *"clearly following deductively from previously accepted ideas and/or interpretation of empirical evidence"* (Taber, 2001b) and, moreover, learners have difficulty appreciating and applying the relationships between the submicroscopic, the symbolic and the macroscopic levels (Johnstone, 1991; Harrison & Treagust, 2000; Taber, 2001b; Dori & Hameiri, 2003). As a consequence, students' tend to construct alternative conceptions to make sense of such abstract concepts, often assimilated with no scientific understanding. These conceptions, which derive from *"the learners' understanding of prior science teaching"* (Taber, 2001b, p. 129), are labeled by Vinner (1997) "pseudo-conceptions" and by Taber (1999) "alternative frameworks". Taber (2003) shows how the chemistry teaching given to students at pre-university level is liable to lead to such conceptions. From their chemistry teaching, students come to consider that atoms are granted "ontological priority" when conceptualizing the world in terms of particle models. Molecules are seen as combinations of atoms (e.g. "a group of atom bonded (joined) together"), and ions are considered to be altered atom (e.g. "an atom which has lost or gained electrons"), rather than being viewed as entities as fundamental as atoms. The brief description above, characterizing the target knowledge set out in the French secondary curriculum provides a clear example of school chemistry may readily lead to such a conceptualization. As a consequence:

- Students often suggest that atoms are indivisible, and *"can not be broken down*", and that *"an atom is the smallest thing in any matter"* (Taber, 1996). Although aware that the atom has a structure, these students are still able to develop a concept of the atom that – if not strictly indivisible – only "lends" out its component parts (i.e. electrons) on a temporary basis (Taber & Watts, 1996).
- Students commonly believe that for ionic bonds, as an anion has an electron "belonging" to a particular cation, there is considered to be some form of special link between them. This leads to learners believing that there are two types of interactions in an ionic lattice: ionic bonds (between ion pairs where transfer has occurred) and "just forces" between ions not having been involved in the electron transfer (Taber, 1994, 1997)

It seems reasonable to consider that learners' ideas of abstract concepts need to develop over extended periods (e.g. Taber, 2004). So, students evolve an alternative conceptual framework whilst trying to adapt their conceptions to the received teaching. That is, as suggested by Gilbert, Osborne & Fensham (1982), they develop what was labelled by Driver (1989) as "intermediate conceptions" or by Vosniadou (1994) as "synthetic mental models". But, such alternative conceptions can act as pedagogical learning impediments rather than a bridge to a more appropriate conceptualization (Taber, 2001a, 2003). It seems that the alternative conceptions about atoms and chemical change that many students (16-18 years old) take into their study of chemistry tend to be of this type.

The study discussed in this paper is a cross-sectional study of the way upper secondary school French students (grade 10 to 12) understand chemical transformation, with particular regards to the changes to the chemical entities (molecules, ions etc.) present, and in terms of intramolecular and/or intermolecular bond breaking. The research questions are:

- What "alternative frameworks" or "pseudo-conceptions" have the students of different age levels been building in terms of (a) the conservation of atoms and/or molecules during chemical transformation and (b) bond breaking?
- Do these conceptions evolve over these different teaching levels, and (if so) how do they evolve?
- Can the notion of the "ontological priority" of atoms, and the consequences that may be seen to follow from it, explain certain of these conceptions?

- How do students take into account the "register of models" at atomic and molecular scale to explain a chemical transformation?

Methodology

The collection of data was undertaken, with the use of a paper-and-pencil questionnaire, from 930 students of different upper secondary schools of the area of Pau (France) at the beginning of teaching: 239 grade 10 students, 422 grade 11 students, and, initially, 269 grade 12 students. All the students in grade 10 were studying chemistry as part of the general school curriculum, whilst those in grades 11 and 12 had selected the natural science stream (‘*série scientifique*’) of the *'baccalauréat général'*. The sample drew upon the three years groups from the same two schools, except for grade 11 where some of the students came from a school not sampled at the other two grade levels. As the National Curriculum must be followed by all teachers in France, and as this school and its teachers were considered similar to the others schools in the study, we can reasonably assume that the three years groups can be compared. The questions asked are available in an appendix (see appendix 1). These questions are part of a more general questionnaire that comprises 14 questions (those discussed here are respectively questions 5, 12, 8, 9 of this questionnaire). A further sample of 158 grade 12 students, from the same schools but the following year, was called for the second question, as it was found that only a minority of students among the initial sample were able to justify their choices. All questions and responses were made in French, the language of instruction, and have been translated into English for this report of the research.

The first question *“How do you see the chemical transformation with regards to the changes within molecules and atoms?”* was asked in order to see if students had grasped the non-conservation of molecules but conservation of ‘atoms’ (end of lower secondary school) or 'elements' (end of grade 10) during such transformation and whether they could apply the concept of chemical transformation in their justifications. Question 2 aimed at exploring to what extent students' associate chemical transformation with the breaking of inter- and intra-molecular “bonds”. For these two questions, the students were initially asked to give their opinion on the different assertions (labelled A, B, C, D in the analysis of results) by choosing one of four responses *1- fully in agreement, 2- somewhat in agreement, 3- somewhat in disagreement, 4- fully in disagreement*. To analyse the evolution in the overall pattern of the students' choices with grades, the choice rates of different answers are calculated, for each assertion and each grade, in relation to the total number of students who have made a choice. A cross-checking of responses to the different assertions has been undertaken to find out the global pattern of students' conceptions related to chemical transformations and the "register of models". In the second part of these questions, students are asked to justify their response in the first part. For these open-ended components of the questions, a multiplicity of student answers was generated. Student responses were then coded according to the main ideas used in the justifications given. All the justifications were classified into one of the discrete categories derived from the analysis; except for a few justifications of grade 10 students in question 2 that included several elements. These were categorised in several response categories. The classification was undertaken by the two first authors independently, who then discussed any disagreement to reach an agreed classification. For the purposes of the analysis we have combined the two response categories agreeing with the statement, and the two disagreeing with the statement, so that we can consider the justifications offered by those agreeing and disagreeing separately.

Questions 3 and 4 were intended to explore to what extent grade 11 and 12 students could use features of the "register of model" in the interpretation of two specific examples of chemical transformations. They have been informed by the Barker and Millar (2000) study concerning the energy change during chemical reaction in relation to chemical bonding. The same process of analysis was used as that for the justifications in the first two questions but here, different facets of explanations have been identified, and it was found that several facets can appear in one single response.

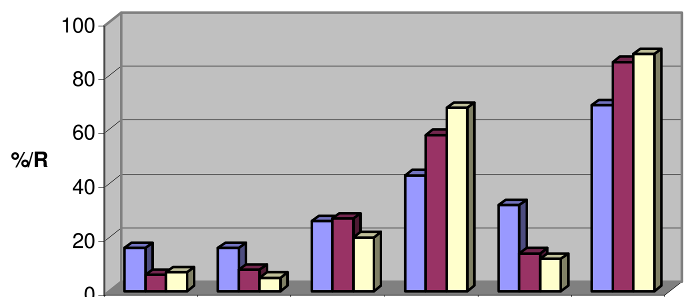
Analysis of results

- Conservation of atoms and/or molecules within chemical transformation?

Assertion A)*: the nature of molecules does not change*

The response rate of answers to the question is high for each sample: grade 10 (93%); grade 11 (96%); grade 12 (95%). Figure 1 allows for the comparison of the evolution of the pattern of students' choices between the four reponse options during the three grades.

Figure 1: Evolution of the students' choices concerning the change of nature of molecules during chemical transformation.



	A1	A2	A3	A4	A1+A2	A3+A4
grade 10	16	16	26	43	32	69
grade 11	6	8	27	58	14	85
grade 12	7	5	20	68	12	88

As the figure shows, the percentages of choices that agree that molecules change during transformation (A3 + A4) are high in each sample (grade 10, 69%; grade 11, 85%; grade 12, 88%) and a positive trend from grade 10 to grade 12 can be observed. This could be explained by the fact that from grade 10 onwards, the concepts of atom, molecule, chemical bond and chemical transformation are used regularly in classes.

Students' justifications:

The number (and percentage) of students providing justifications for their choices (A1 or A2 or A3 or A4) were: grade 10, 122 (57%); grade 11, 269 (67%); grade 12, 165 (65%). We have combined the two response categories agreeing with the statement, and the two disagreeing with the statement: A: number of conceptions found in the justifications provided for those agreeing with the statement "During chemical transformation the nature of molecules is not changed" (response options A1 & A2); D: number of conceptions found in the justifications provided for those disagreeing with the statement "During chemical transformation the nature of molecules is not changed" (response options A3 & A4)

The results of the analysis are given in table 1:

In this table, the category of 'new product' refers to justifications of responses in terms of something new being formed during a chemical transformation, whether that something is at the level of a new substance (macroscopic level) or new molecules or ions etc (molecular level).

Table 1: Students' justifications concerning the "change" of nature of molecules during chemical transformation

Justification in terms of:		Grade 10			Grade 11			Grade 12		
		A	**D**		**A**	**D**		**A**	**D**	
new product	Macroscopic level	1	8	*8%*	2	56	*23%*	1	29	*18%*
	Molecular level	1	10	*11%*	3	49	*20%*		20	*12%*
Breaking of the molecule		1	12	*13%*	1	45	*18%*	1	32	*20%*
Reorganization of atoms within molecules		-	31	*33%*	4	29	*12%*	-	23	*14%*
Conservation of atoms		1	4	*4%*	5	20	*8%*	-	8	*5%*
Modification of electronic structure of atoms		1	4	*4%*	3	6	*2%*	-	13	*8%*
Confusions	inter/intra	3	4	*4%*	1	23	*9%*	-	10	*6%*
	atom/molecule	1	3	*3%*	-	1		-	1	
	Chemical reaction = mixing/separation	11	16	*17%*	3	10	*4%*	1	2	*1%*
	Conservation of molecules	5	1	*1%*	-	1			2	*1%*
	Miscellaneous	2	2	*2%*	-	7	*3%*	1	21	*13%*
Total		27	95		22	247		4	161	

D: number of students disagreeing (i.e. thinking that the nature of molecules does change) also given as a percentage of those offering a justification for their disagreement.

A: number of students agreeing (i.e. thinking that the nature of molecules does not change). As this number is very low, the percentage has not been calculated.

Students who consider that the nature of molecule change (D category).

Some justifications are simply formulated in terms of there being some kind of new product (grade 10, 19%; grade 11, 43%; grades 12, 30% of responses were in this category) either at the macroscopic level *("reactants are turned into products")* or at the microscopic level (*molecules change / modify…to produce new molecules*). It may seem surprising, considering the progression in the curriculum, that the difference between the rate of justifications at macroscopic level and that of justification at molecular level increases from grade 10 to grade 12 (-3%, +3%, +6%).

Other students justify their choices in terms of the breaking of the integrity of the original molecule *(molecules split up / divide / destroy themselves; bonds between atoms within the molecule are broken*) (13%, 18%, 20%) or in terms of reorganisation of atoms within molecules (33%, 12%, 14%). Where the increase in the proportion taking into account the breaking up of molecules agrees with the progression of the curriculum knowledge, the decrease in justifications in terms of the reorganisation of atoms seems paradoxical considering that the curriculum for grade 10 insists on the subject. These two categories of justification, that can be considered as an appropriate assimilation of the teaching model of chemical transformation at the microscopic level, are collectively used more during grade 10 after lower secondary teaching (45%) than after completing grade 10 teaching in grades 11 (30%) and 12 (34%).

One of the principles that should be acquired at the end of lower secondary school in France is that when a chemical reaction occurs, atoms are conserved. (Students should consider that it is "elements" that are conserved by the end of grade 10). The principle of conservation, which is sometimes formulated by students in terms of "*nothing is lost, nothing is created, and all is transformed"*, is visible in some justifications, especially in grade 11: *"atoms are conserved, they can be found again in products", "identical atoms can form several molecules"*.

The French grade 11 curriculum emphasises the principle that chemical transformations all imply the redistribution of electrons on the outer shell of atoms. Such explanations were found in our data in terms of: *"electrons divide with the atoms that differ from the origin or move on to another molecule", "atoms lose or gain one (several) electron (s) (to produce ions)*". Such justifications were chiefly found in the responses of grade 12 students. .

- Students who consider that the nature of a molecule does not undergo any change (A category).

Among the given justifications of those agreeing with the statement, many grade 10 students give an interpretation of chemical transformation:

- Either in terms of molecules mixing or associating: *"molecules mix with other molecules"*, *"molecules can associate to one another"*, *"molecules assemble or gather…"*

- Or in terms of molecule conservation: *"Molecules remain identical (keep their nature) but there are many, different or identical, that unite", "Neither the nature of atoms nor that of molecules change, but new bodies can appear".*

These conceptions do decrease during schooling, but they can still be found in grades 11 and 12. They are *also* used to justify the change in the nature of molecules. In accordance with previous studies, this could mean that, for such students, a chemical reaction is a process of "modification" that leads to the juxtaposition (addition, gluing) of the molecules of the reactants.

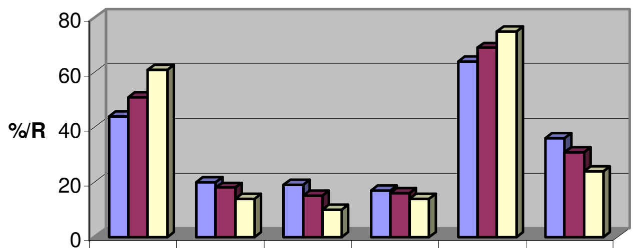
Lastly, some students confuse inter- with intra-molecular bonds in their justification (6%; 9%; 6%)

Assertion B)*: the nature of atoms does not change.*

The number of students (and the percentage of the sample) answering this item for each year group was: grade 10, 213 (89%); grade 11, 398 (94%); grade 12, 251 (93%). Figure 2 allows for the comparison of the progression of choices across year groups. Rates have been calculated according to the number of students who have made a choice.

In this question, the interpretation of the students' choices is more delicate, taking account of taught knowledge. For grade 10 students, choices corresponding to answers B1 and B2 must be considered correct since the assertion corresponds to the received knowledge. But students in grades 11 and 12 are supposed to take into consideration the modification of the electronic structure of the outer shell of atoms. It is no longer atoms but "elements" that are conserved.

Figure 2: Evolution of the students' choices concerning the change of the nature of atoms during chemical transformation.



	B1	B2	B3	B4	B1+B2	B3+B4
grade 10	44	20	19	17	64	36
grade 11	51	18	15	16	69	31
grade 12	61	14	10	14	75	24

Yet, as seen in Figure 2, for most students, it is the atoms that are conserved during chemical transformation, and in view of the progression in teaching it seems paradoxical that this percentage increases from grade 10 to grade 12. This may be a situation where the "ontological priority" of atoms (Taber, 2003) is operating.

Students' justifications:

The number of justifications offered and the percentage of those answering this question offering a justification were: grade 10, 98 (46%); grade 11, 311 (78%); grade 12, 137 (54%). Grade 12 students seem to feel as helpless as those in grade 10 when asked to justify their choices. The results of the analysis are displayed in table 2.

Table 2: Students' justifications concerning the "change" of the nature of atoms during chemical transformation

Justification in terms of:		**Grade 10**		**Grade 11**		**Grade 12**	
		A	**D**	**A**	**D**	**A**	**D**
Modification in the electronic structure of atoms	Bonds formation	-	-	*2*	*2*	*3*	*1*
	Ions formation	*8*	*16*	*32*	*67*	*11*	*27*
	Total	8 *13%*	16 *42%*	34 *16%*	69 *72%*	14 *14%*	28 *72%*
Atom reorganization		22 *37%*	13 *34%*	23 *11%*	3	14 *14%*	3
Atom conservation		29 *48%*	-	154 *72%*	13 *14%*	53 *54%*	2
Confusions Inter/intra		1	1	2	1	1	-
Miscellaneous		-	8 *21%*	2	10 *10%*	16 *16%*	6 *15%*
Total		60	38	215	96	98	39

D: number of students disagreeing (i.e. thinking that the nature of atoms does change) also given as a percentage of those offering a justification for their disagreement.

A number of students agreeing (i.e. thinking that the nature of atoms does not change), also given as a percentage of those offering a justification for their agreement.

- Students who consider that the nature of atoms changes (D category).

Most justifications provided for this category are formulated in terms of modification of the electronic structure of atoms (42%, 72%, 72%). Such modification mostly results in the transformation into ions (or loss / gain of electrons) and, to a small extent, in the formation of bonds.

It must be noticed that among grade 10 students who consider that the nature of atoms changes in the course of chemical reaction, a significant proportion justifies this point of view in terms of atomic reorganisation. It could be that some students intuitively sense the reorganisation of atoms goes with certain modifications, e.g. in their electronic structure, but without further investigating this issue (e.g. through in-depth interviews) this must remain a conjecture to be explored in future research.

- Students who consider that the nature of atoms does not change (A category).

For some of the concerned students, the nature of atoms does not undergo any change even if their outside electronic structure can vary (13%, 16%, and 14%). One can suppose that such students implicitly identify the expression 'nature of atoms' with the core of the atoms, i.e. to that used to define the element, seeing changes in the outer electronic arrangement as superficial. Alternatively, for some students structures such as the molecule and ion are seen as transitory arrangements through which the atom may pass, before returning to its "natural state" with its original set of electrons (Taber & Watts, 1996).

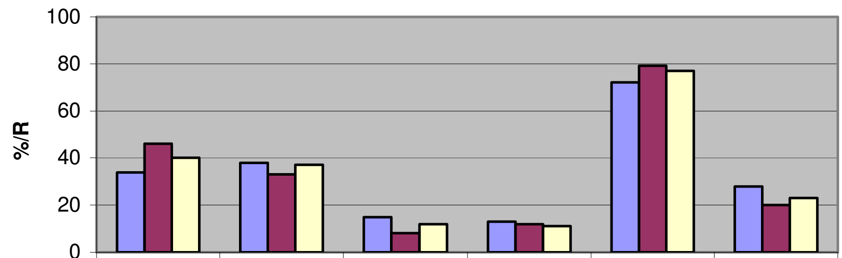
Many students write that atoms are conserved (respectively 48%, 72%, 54%) for the justification in this category). For these students, from grade 10 to grade 12, it is certain that *"an atom is an atom and it never changes*", *"atoms are the basis of molecules, they cannot be divided"*, *"one can find the same atoms in reactants and products*". Lastly, the conservation of the nature of atoms can at times be justified by the conservation of their number (for instance, such an argument accounts for some 15% of the justifications provided by the students in grade 11), often as *"nothing is lost, nothing is created"*. To the idea of transitory states of atoms which none-the-less conserve their identities when they form new molecules and ions, we can add the application of the macroscopic "principle of conservation" at atomic and molecular scales. If *"nothing is lost, nothing is created"* it is not surprising that students think that an atom never changes.

- Breaking of inter and/or intra-molecular "bonds" during chemical transformation?

Assertion C): *During chemical transformation, inter-molecular bonds (between molecules) are broken.*

The number of responses to this item (and the percentage of the sample responding) were: grade 10, 198 (83%); grade 11, 390 (92%); grade 12, 380 (first and second sample because they are no great difference between their choices) (89%). Figure 3 shows the progression of the students' choices over the school years (grade levels). Rates have been calculated according to the total number of students who have made a choice.

Figure 3 : Evolution of the students' choices related to the breaking of intermolecular bonds during chemical transformation



	C1	C2	C3	C4	C1+C2	C3+C4
grade 10	34	38	15	13	72	28
grade 11	46	33	8	12	79	20
grade 12	40	37	12	11	77	23

To interpret the choices at the different levels, it is necessary to refer to the target knowledge presented in the curriculum. During grade 10, the concept of the covalent (intra-molecular) bond is introduced. Chemical transformation is interpreted in terms of breaking and forming of such bonds and of the reorganisation of atoms from reactants to products. At the end of grade 11, for a chemical reaction between gaseous substances (the reactions of combustion are taken as examples), calculations based on the energetics of breaking and forming intra-molecular bonds leads to the determination of heat (enthalpy) of reaction. For the molecular compounds, the changes of state are interpreted in terms of modification of inter-molecular interactions. The energetic balance that leads to the determination of the heat (i.e. enthalpy) of a chemical transformation (for example the combustion of liquid ethanol) taking into account the two types of bonds is not specified in the National Curriculum.

One should therefore expect to witness an increase in the level of understanding of these two types of "bond" and their being increasingly taken into account when interpreting the two types of transformation. The results show that the majority of students agree that there is breaking of inter-molecular "bonds" during a chemical transformation (C1 + C2) at all three levels (72, 79, and 77%). It is obviously a satisfactory answer when considering the linking between the macroscopic and the atomic or molecular levels. Nevertheless, it is only through the students' justifications that we are able to go further in interpreting students' thinking.

Students' justifications:

The number of students (and percentage of those answering this question) able to offer a justification of their responses in the three year groups (grade levels) was: grade 10, 83 (42%); grade 11, 105 (27%); grade 11 (second sample 82; 52%). So, only a minority of students are able to justify their choices. To explain such a low rate, one can either suppose the students feel incompetent to do so, or consider the effect of weariness linked to the place of the question within the more general questionnaire (12th out of 14 questions). Yet one should notice that questions 13 and 14 of the original questionnaire have obtained a higher rate of answer: 42%, 66%, 52% and 64%, 55%, 36% respectively. The low rate of justifications of grade 12 students on the first sample (15, i.e. 7%) led us to ask another sample the second question of the appendix 1 only. The noticeable increase of justifications leads us to assert that the effect of weariness is one relevant factor, even if the first hypothesis should not be excluded. The justifications of this second sample will be analysed in the continuation of the study. Table 3 reports the results of the analysis of justifications.

The different categories of prominent justifications are as follows:

- Disagreement because': "*there is no bond between molecules, but it exists between atoms",* in accordance with Taber's finding (1993), or *because* "*the breaking of the bond concerns only the change of state*";
- It is considered possible only if there is a phase change during transformation (12% in grade 12).
- Conception that "*the molecules should be separated to react and produce new molecules*". This idea, taking into account the global conception of chemical transformation, increases across the successive grade levels (11%, 33%, and 44%);

Table 3: Students' justifications for the "breaking" of intermolecular bonds during chemical transformation

Justification		Grade 10			Grade 11			Grade 12		
		A	D	T%	A	D	T%	A	D	T%
No idea of breaking	There exist no bond between molecules	3	2	**6**	3	16	**18**	-	5	**6**
	Breaking is saved for state changes	-	1	**1**	-	-	**-**	-	4	**5**
	Bonds remain the same	1	9	**11**	-	1	**1**	-	-	**-**
Idea of breaking only if there is a phase change during transformation		3	2	**6**	1		**1**	6	4	**12**
With idea of breaking	In terms of reaction between molecules.	9	1	**11**	30	4	**33**	32	4	**44**
	In terms of separation	17	2	**21**	17		**16**	-	-	**-**
Confusion	Inter / intra bonds	22	10	**36**	27	3	**29**	22	3	**32**
	Chemical transformation and change of state.	3	1	**4**	-	-	**-**	-	-	**-**
Miscellaneous		3	1	**4**	1	1	**1**		2	**2**

A: number of students justifying their agreement (i.e. thinking that during chemical transformation, inter-molecular bonds are broken)

D: number of students justifying their disagreement (i.e. thinking that during chemical transformation, inter-molecular bonds are not broken)

T: as a percentage of students offering justifications for their agreement or disagreement-

- Simple mention of the "*molecule getting loose / separating / dispersing*" (Grade 10, 21%; grade 11, 16%), a formulation that can be interpreted as a confusion between physical and chemical transformations;

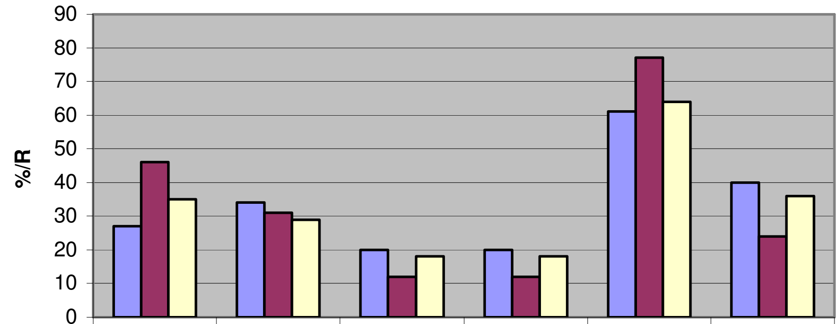
- Confusion between inter and intra-molecular bonds (accounts for around 33% of students at each level). Such confusion is seen in the following terms: "*bonds break to produce new bonds / new* molecules" or "atoms reorganise and are shared around". This is despite the question offering the clarification that inter-molecular bonds were 'between molecules'.

Assertion D): *during chemical transformation intra-molecular bonds (between atoms in the molecule) are broken*

The number and rate of choice of this assertion for each sample were: grade 10, 189 (79%); grade 11, 378 (90%); grade 12, 375 (88%). Figure 4 allows for the comparison of the students' evolution in the choices in the course of learning.

One can note that the percentage of students who agree with that proposition is relatively high and reaches its peak at the beginning of grade 11 (after teaching about covalent bonds). Nevertheless it can be observed that students are rather shy when asserting such agreement; the percentages of D1 and D2 choices do not differ much. Last, one can be surprised that about 1/4 of grade 11 students and 1/3 of grade 12 do not consider the breaking of intra-molecular bonds during chemical transformation in spite of fact that almost all the examples seen during teaching (in gas phase, in aqueous solution – acid-base and oxidation-reduction) involve the breaking (in some reactants) and the forming (in some products) of such bonds..

Figure 4 : Evolution of the students' choices on the breaking of intra-molecular bonds during chemical transformation.



	D1	D2	D3	D4	D1+D2	D3+D4
grade 10	27	34	20	20	61	40
grade 11	46	31	12	12	77	24
grade 12	35	29	18	18	64	36

Students' justifications:

Their numbers and rates are again very low: grade 10, 62 (33%); grade 11, 102 (27%); grade 12, 72 (48%). The results of the analysis of justifications are displayed in table 4.

Table 4: Students' justifications for the "breaking" of intra-molecular bonds during chemical transformation

Justification		**Grade 10**			**Grade 11**			**Grade 12**		
		A	**D**	**T%**	**A**	**D**	**T%**	**A**	**D**	**T%**
Without idea of breaking	Molecules remain the same / atoms remain linked / remain the same	1	5	**8**	9	3	**12**		13	**18**
	Chemical transformation has no stake on these bonds		1	**1**	1		**1**		3	**4**
With the idea of breaking	In terms of atom reorganisation	24	2	**36**	34	2	**35**	21		**29**
	In terms of nature change in the molecules	13	1	**19**	47		**46**	16		**22**
	In terms of chemical transformation	2		**3**	1		**1**	13		**18**
Confusion	Inter / intra bonds	1	1	**3**	2		**2**	1	2	**4**
	Chemical transformation and change of state	1	3	**6**						
	Atom / molecule	5	7	**17**					1	**1**
Miscellaneous		3	2	**7**	1	2	**3**		2	**3**

A: number of students justifying their agreement (i.e. thinking that during chemical transformation, intra-molecular bonds are broken)

D: number of students justifying their disagreement (i.e. thinking that during chemical transformation intra-molecular bonds are not broken)

T: as a percentage of students offering justifications for their agreement or disagreement

As table 4 shows, most students who consider the breaking of intra-molecular bonds to occur during chemical transformations, give a justification, either in terms of atomic reorganisation: "*atoms get loose / move / undergo a change of place / reorganise*", "*atoms* *will produce new molecules bonds must break*", or in terms of a modification in the nature of molecules: *"molecules change to create a new molecule"*, "*reactants → products".*

Yet, for some students, there is no breaking of intra-molecular bonds during transformation (9%, 13% and 22%): "*intra-molecular bonds are not broken / atoms remain linked / together", "molecules remain the same*". It is paradoxical that the percentage should increase with grade level.

Only grade 10 students confuse atom with molecule in a noticeable number.

The concept of intra-molecular bonding, and the taking into account of its breaking during chemical reactions, seems therefore to be mastered by a majority of students, although about third of grade 12 students do not believe such bond breaking to be integral to chemical change.

- Cross-checking of choices to assertions A, B, C and D.

We have tried to find out about the students' global description of chemical transformation in terms of conservation of atoms and molecules as well as in terms of breaking of inter and / or intra-molecular bonds. To do so, we have analysed the choices produced by the students who have made a choice in all the assertions. We have again grouped together, on the one hand, the choices *"fully in agreement"* and *"somewhat in agreement"*, on the other hand, the choices *"somewhat in disagreement"* and *"fully in disagreement"*. The results are reported in table 5.

Table 5: Students' description of chemical transformation with the "register of models"

Category		Grade 10		Grade 11		Grade 12	
		N	%	N	%	N	%
Change for molecules and not for atoms	Breaking of inter and intra molecular bonds	30	17	150	42	73	36
	Breaking for inter, not for intra	29	16	54	15	40	20
	Breaking for intra, not for inter	20	12	42	12	24	12
	no breaking for inter and intra	4	2	5	1	3	2
Total 1		**83**	**48%**	**251**	**70%**	**140**	**70%**
Molecules and atoms are modified	Breaking of inter and intra molecular bonds	21	12	32	9	21	11
	Breaking for inter, not for intra	8	5	11	3	5	2
	Breaking for intra, not for inter	3	2	11	3	7	3
	no breaking for inter and intra	4	2	3	1	3	2
Total 2		**36**	**21%**	**57**	**16%**	**36**	**18%**
Molecules do not change	atoms do not change	36	21	30	8	17	8
	atoms change	17	10	19	5	8	4
Total 3		**53**	**31%**	**49**	**13%**	**25**	**12%**
TOTAL GENERAL		**172**	100%	**357**	100%	**201**	100%

N: number of students in agreement with this global description

Three categories of descriptions of chemical transformation with the "register of models" can be identified:

- ***"The molecules change but atoms do not change"***. A large majority of grades 11 and 12 students have this idea (70%). This conception is generally associated with the breaking of inter and intra molecular bonds (about 40% of this students). The other students seem not to have a clear view of the way these bonds are involved in chemical transformation. Yet, we note that 16% of grade 12 students of this category say that there is no breaking of intra-molecular bond when molecules are modified. Among grade 10 students, after chemistry teaching at lower secondary, fewer (48%) share this general idea that molecules, but not atoms, change in chemical transformation. As the notion of chemical bonds has not been taught at this level, it is not surprising that there is no clear preference for any particular option in relation to which type of bonds are disrupted.

- ***"Molecules and atoms change"***. Only about 20% of students of all grades have this conception. We can also note that the percentage of students who share the global conception of chemical transformation (change of molecules and atoms and breaking of inter and intra-molecular bonds) is low (about 10%) and remains approximately constant throughout the grade levels.

- ***"Molecules do not change"***. Approximately one third of grade 10 students have this conception (some believing that atoms change, some believing neither atoms nor molecules change in chemical transformations), and even at grades 11 and 12 about an eighth of the students report this belief. We think that this idea can also be explained by the application of the "**conservation principle"** as a heuristic principle of thinking.

- The linking between the "empirical register" and the "register of models".

We now turn to consider the two questions asking students about specific examples of changes.

a) ***Forming of sodium chloride***: *how can the change of solid Na and gaseous Cl_2 into solid NaCl be explained?* (question 3)

We expected some explanations such as: bonds between atoms in metal sodium have been broken; covalent (or intramolecular) bonds in chlorine molecules have been broken; ions Na^+ and Cl^- have been formed; ions are held together by electrostatic interactions to form ionic crystal; etc.

The number and rate of responses to question 3 were: grade 11, 261 (62%), grade 12 (first sample), 119 (44%). The results of the analysis are shown in table 6.

Many answers include the writing of an equation for the reaction, either by itself or accompanying the interpretation. Thus our two-fold analysis: the writing of the equation of reaction and the interpretation of chemical transformation.

Table 6: Students' explanations of NaCl formation

		Grade 11		Grade 12	
		N	%	N	%
Writing of equation of reaction	Correct $2Na + Cl_2$ ($Na + {}^{1}/_{2}Cl_2$) $\rightarrow$ 2 NaCl (NaCl or $Na^+ + Cl^-$)	51	**35**	31	**51**
	Not correct : formula of composition of chemical species ($NaCl_2$, Na_2Cl_2,…)/ wrong ion charges (Na^{2+}, Cl^{2-})	39	**27**	6	**10**
	Not correct: coefficients were not adjusted	28	**19**	12	**20**
	Not correct : ions identified as reacting species: $Na^+ + Cl^-$ ions $\rightarrow$	21	**14**	9	**15**
	Not correct : call for outside species (O_2, H_2O, CO_2)	7	**5**	3	**5**
	Not correct : miscellaneous (dissociation) NaCl $\rightarrow Na^+ + Cl^-$	1	**1**	-	**-**
	Total	**147**		**61**	
Facets of explanations	Simply in terms of chemical reaction (between ions, between atoms or molecules, transformation, redox reaction, combustion)	140	**54**	52	**44**
	Simply in writing an equation of reaction	55	**21**	41	**34**
	Bonds taken into account	23	**9**	6	**5**
	Use of ions	24	**9**	2	**2**
	In energetic terms, heat, temperature, stability	14	**5**	1	**1**
	In terms of transformation of chemical species	20	**8**	1	**1**
	In terms of combination / association/ absorption/ addition/ regrouping/ linking/ attraction	30	**11**	5	**4**
	In terms of changing of state of one or several bodies	20	**8**	2	**2**
	In terms of mixing /contact/ affinity (alchemy)	7	**3**	2	**2**
	In terms of «transmutation »: a body turns into another / produces from smoke/ disappears	4	**1**	-	**-**
	Miscellaneous: Conservation	8	**3**	1	**1**
	Miscellaneous: others	4	**1**	1	**1**
	Total	**349**		**138**	

N: number of students who have given this facet of explanation
The percentages for the facets of explanations have been worked out in accordance with the number of answers given to the question (many responses included more than one of explanatory facets).

Writing of the equation of reaction

Among the 147 students who choose to write an equation of reaction, an increase in the proportion giving the correct equation can be witnessed between grade 11 and grade 12. Yet the rates are weak (35% grade 11 and 51% grade 12). The main errors concern:

- A non-correct writing of the formula of the composition of chemical species or non-correct charge of ions. This type of error diminished between the two levels considered;
- Identifying ions as being the reacting species;
- Erroneous adjusting of the coefficients of equation: a fifth of the written equations among both grade 11 and grade 12 students included errors if this type;
- And, even though the rate is low, the involvement of species that do not belong in the reaction is observed.

It can be concluded that the symbolic representation of a chemical reaction with the equation of reaction is far from mastered by many students at these grade levels.

Interpretation of the chemical transformation

We note that about 75% of the students are satisfied with an explanation at macroscopic level simply in terms of chemical reaction. They either write *"there is a* *chemical reaction"*, with or without specifying the reactants and products; or they categorize the type of reaction (redox, combustion, and even acid-base); or else they simply write the equation of reaction.

Few of students give an explanation using the "register of models" at atomic or molecular level, and for those who do, the use of this register is usually erroneous. There are few examples of formulation which are accurate:

- Taking the bonds into account: "*Na links to Cl (or Cl_2)*", "*Cl_2 molecules divide into two Cl atoms that link individually to one Na atom to produce solid NaCl",* but this bond is most of the time considered to be covalent: "*one Cl atom links to one Na atom by a covalent bond and one solid NaCl forms*", *"linked electron pairs of Na and Cl atoms attract to link, which produces NaCl*", "*an exchange takes place between electrons to constitute a molecule*".

- The forming of an ionic compound: e.g. "*there exists a transfer of electrons*"; "*Na^+ attracts Cl^- to form a neutral solid*"; "*Chlorine molecules will unite with the sodium molecules. There may be an attraction due to the opposing signs of the two molecules*", "*an ionic crystal has formed*". This ionic compound can be a precipitate: "*The piece of Na dissolves in the Cl_2 and forms a solid precipitate*".

- The energetic aspect: examples include "*Due to heat and fire, gaseous Cl_2 and solid Na have been consumed so as to obtain solid NaCl*"; "*the Na and Cl_2 molecules touch and react to one another to form NaCl, the heat accelerates the movement of molecules, which leads to a violent reaction*"; "*the heat breaks bonds to form solid NaCl"; and "NaCl is more stable than Na and Cl_2*".

We also note that a significant number of students express their answers in terms of combining / associating or changing of the chemical species, especially at the beginning of grade 11: e.g. "*atoms combine / associate to one another*"; "*molecules come together*"; "*Cl_2 fastens to Na which results in the forming of solid NaCl*"; "*The chemical elements have undergone a transformation*"; "*the molecules assemble differently": "the piece of Na has somewhat been de-clustered by fire, the Na molecules will reorganize around the chlorine"; etc.*

In these different explanations the "ontological priority" of atoms and the conception of transformation as a simple modification of molecules by juxtaposition or gluing appear.

b) Forming of hydrochloric acid: *how can the formation of hydrochloric acid from hydrogen chloride and water be explained?* (question 4)

The modelling of the dissolution of hydrogen chloride into water leading to the formation of dissociated hydrochloric acid is presented at the beginning of grade 11, and the

Brønsted-Lowry model of acid – base reactions are taught in the middle of the grade. At the end of grade 11, students are expected to know:

- *How to write the equation of reaction associated with the dissolution into water of a species* (one of which is HCl) *that leads to an electrolytic solution;*

- *How to write the equation of an acid-base reaction* (including the dissociation of HCl into water).

So, the elements of expected explanation are: Hydrogen chloride dissolves into water, the polar water molecules interact with polar HCl molecules, the interactions lead to the breaking of covalent (or intra-molecular) H-Cl bonds and the formation of hydrogen (or hydronium) and chloride ions, which are solvated and dispersed in a solution.

The number and rates of responses to that question among the sample were: grade 11, 345 (82%); grade 12, 149 (55%). An overview of the outcomes of the analysis of responses is displayed in table 7.

Table 7: Students' explanations of hydrochloric acid formation

		Grade 11		Grade 12	
		N	**%**	**N**	**%**
Writing of reaction of equation	Correct writing of the formation of ions	148	**64**	106	**77**
	$HCl_{(g)} + H_2O \rightarrow HCl_{(aq)} + H_2O$: no significant interaction	73	**32**	16	**12**
	Non correct formulation of chemical species ($HClO$, H_3ClO, H_3Cl, H_2Cl, HCl_3)	51	**22**	11	**8**
	Unknown bodies are present	19	**8**	4	**3**
	Ions are already initially present	6	**3**	-	-
	Total	**231**		**137**	
Facets of explanations	By simply writing an equation of reaction	213	**62**	124	**83**
	In terms of mixing or dissolution or ionic solution	65	**19**	10	**7**
	In terms of hydration or dissociation	36	**10**	12	**8**
	In terms of dissociation - hydration - dispersion	10	**3**	-	**-**
	In terms of reaction or transformation or interaction	15	**4**	2	**1**
	In terms of reorganization of ions or interaction between ions	5	**1**	-	**-**
	In terms of bond between HCl and H_2O	9	**3**	-	**-**
	Miscellaneous	7	**2**	-	-

N: number of students who have given this facet of explanation
The percentages for the facets of explanations have been worked out in accordance with the number of answers given to the question (several different facets of explanations can appear in one single description)

Here again a large proportion of students in both grades have decided to model transformation at macroscopic level by writing an equation for the reaction although (67% and 92%). There is a definite improvement between the grades in terms of the proportion of the equations judged correct (64% vs. 77%). Nevertheless, it is surprising to notice that some grade 12 students consider water as a substance that does not take part into the reaction (as Boo & Watson, 2001, note) and that some of them make errors when writing the formula of chemical substances or rely on substances that are not part of the system (OH^-, O, O_2 in the products).

The given explanations very often take the simple guise of the writing of an equation for the reaction. When further explanations are provided, it is the dissolution that is often the focus: "*when in contact with water, the hydrogen chloride dissolves and ions are made up*".

Some students discuss hydration or solvation of ions: "*Hydration (or solvation) of ions which results in the making up of hydrochloric acid*". Some consider the breaking of the H-Cl bond under the action of water: "*water splits the hydrogen atom from the chlorine atom to form* H^+ *and* Cl^- *ions*" and only three grade 11 students can explain the mechanism of ion formation rather more satisfactorily: "*the water molecules, because they are polar attract and separate H and Cl atoms, thus forming* H^+ *and* Cl^- *ions*". Yet, at grade 11 level, some also simply introduce the three steps of the dissolution of electrolytes "*Dissociation - Hydration - Dispersion*". (Although the questionnaire was undertaken at the start of the academic year, it is possible that these students have already received teaching about this topic.)

Therefore, once again, assimilated knowledge often appears somewhat distant from the target knowledge presented in the curriculum, and the equation for a reaction is often considered sufficient to explain the chemical transformation.

Discussion

Many students that enter grade 10 interpret the chemical reaction in terms of mixing or associating of molecules, and nearly a third of them believe that the nature of molecules does not change in the course of transformation. From grade 10 to grade 12 the proportion of students responding in this way dropped to about an eighth of the sample. The justifications provided by the students who take the opposite view only seldom consider the microscopic level, especially the breaking of bonds within the molecule and/or the reorganization of atoms (such answers making up only a third of the responses even among the students in grade 12).

There is an increase in the number of students who argue from a principle of the conservation of the nature of atom from grade 10 to grade 12. This could mean that the "immaterial" concept of element that has been introduced at grade 10 level does not easily replace of the already familiar notion of the atom. When a change in the electronic structure is considered, it is nearly always as the consequence of the transformation of atoms into ions rather than as the forming and/or breaking of bonds.

Generally, chemical transformation is interpreted at sub-microscopic level by the majority of students as *the molecules change but the atoms do not change*, and this is generally associated with the breaking of inter- and intra-molecular bonds. However, the implication of bond breaking/making is not clear in the minds of many students, and more than one third of grade 12 students do not consider the breaking of intra-molecular (i.e. covalent) bonds during a chemical transformation.

Two sorts of "alternatives framework" (or "pseudo-conceptions") can explain such ideas:

- First, the "ontological priority" of atoms (Taber, 2003). If atoms are seen as fundamental building blocks of matter, they can be rearranged in chemical transformation but they are conserved. As writes one student: *"An atom is an atom and it never changes!"* Even if the electronic structure is taken into account, the structural modification of atom is seen as only superficial or transitory: it "lends" one electron before returning to its initial state. Progression in the French curriculum involves learning about the changes in electronic structures that accompany chemical change and so the notion of 'element' is introduced at this point, with the sense of what is common between the chemical element (in its English sense) and its compounds. This notion can provide an abstract way of thinking about what remains constant in chemical changes. However, where students retain a concept of the atom as immutable, and apply this in their mental modelling of chemical transformation, there is little incentive to adopt the abstract concept of "element".
- Our second hypothesis is the transfer of the macroscopic "conservation principle" (*"nothing is lost, nothing is created, everything changes*") to the atomic and molecular levels. This maxim is present in the mind of many students. If *"nothing is lost",* then neither atoms nor molecules change; if *"nothing is created"* then it is impossible to create new molecules by the rupture of intra-molecular bond and the rearrangement of atoms; and since *"everything changes*" the change can be explained by the mixing, gluing, binding of initial atoms or molecules. The additive (rather than inherently bonded) conception of the molecule is therefore justified, providing a parallel at the molecular level of the students' "mixing/separation of substances" model of chemical transformations (Anderson, 1990; Hesse & Anderson, 1992; Ramsden, 1997; Laugier & Dumon, 2003). For example, if water appears during chemical transformation it is because it is initially present in the reagents.

The difficulty many students appear to have taking into account ionic and molecular interactions to explain the combustion of sodium in chlorine and the dissociation of hydrogen chloride into water can be explained by another "ontological priority" linked with the teaching given: the ontological priority of covalent bond. It has been suggested that when this is introduced first it provides a template or schema, which is then used by students as the basis for making sense of other bond types (Taber, 2001b). In the French curriculum, there is extensive teaching about the covalent bond in grade 10 and the other bond types are briefly introduced in grade 11. So, to explain the $NaCl_s$ formation, several students write: "*one Cl atom links to one Na atom by a covalent bond and one solid NaCl forms*"; "*electron pairs of Na and Cl atoms attract to link, which produces NaCl*"; "*an exchange takes place between electrons to constitute a molecule*". Furthermore, the alternative framework of the "octet rule" leads many students to give a Lewis representation of the $NaCl_s$ entity

and assume that ionic bonds exist between these molecules (Butts & Smith, 1987; Taber, 1994; Boo, 1998; Tan & Treagust, 1999; Cokelez & Dumon, 2005b). In the face of these difficulties with assimilating and adopting the microscopic scale of the "register of models", many students are often satisfied (or at least, prepared to limit their answers) to modeling the change at macroscopic scale through a chemical equation. We can add that the writing of an equation for a chemical transformation that has not necessarily been taught (combustion of sodium into chlorine) is problematic to many students, whereas the writing of an equation of reaction that has been previously taught is easier.

In terms of the evolution of knowledge with grade level, it seems that grade 11 students have assimilated the concept of covalent (intra-molecular) bond taught in grade 10, but once this concept is not explicitly studied any longer; many students go back to their initial level of understanding. On the other hand, the teaching of ionic and inter-molecular interactions, and the energetic cohesion of matter, in grade 11, seems to have no great influence on the answers of grade 12 students. It seems that much of the taught "register of models" does not seem to get strongly integrated into long term memory.

Conclusion: *Educational implications*

In this paper we have reported findings from a study which has explored how secondary level French students understand chemical transformations in relation to the abstract concepts of the 'register of models' presented in the curriculum: in terms of atoms, , 'elements', molecules and ions, and in terms of the breaking and forming of different classes of bond. It is clear that many students are not able to provide explanations that match the target knowledge presented in the curriculum. It is also clear that, in spite of the specificity of the French curriculum, in many respects the difficulties these students face are similar to those previously reported from studies undertaken with secondary age students in other educational settings. This reiterates the inherent difficulty of many of the abstract ideas at the heart of chemistry. The finding of similar learning difficulties across different educational and linguistic contexts supports a view that many of these difficulties may be associated with the abstract and theoretical nature of the subject matter, and this present study offers evidence from one such context to supplement existing literature.

However, the present study has also been able to suggest how certain difficulties can be linked to the specifics of the teaching these students have faced. Aspects of the timing and sequencing of the French curriculum, particular features of the French language used as the medium of instruction, and specific features of the French chemical idiom (the way 'element' is used, the widespread use of the motto *"nothing is lost, nothing is created, everything changes*" can be related to the specific patterns of responses found among these French students. Although in general terms, these French students experience similar learning difficulties to those reported for their peers in other countries, some of the particular features of the patterns in responses elicited here, which have not been reported elsewhere, would seem to be linked to aspects of the French curriculum. We have been able to highlight specific features of the teaching in French schools which may act as 'pedagogic learning impediments' (Taber, 2004) and which should be brought to the attention of teachers in France. Further comparative research in other educational contexts would be valuable to explore whether the specific patterns of learning difficulties in other countries can be associated with particular linguistic or pedagogic features. As one example, it would be useful to identify other educational contexts where mottoes such as *"nothing is lost, nothing is created, everything changes*" are widely used, and to find out whether they have a similar influence on student learning in those other contexts.

Like Taber (2004), we have noticed that, during the first confrontation with abstract knowledge, students have difficulties integrating it into their conceptual schemes. It is not surprising! For example, when one presents the hydrogen chloride molecule under the form of HCl and the crystal of sodium chloride under the form of $NaCl_S$, how can a student realize that important differences hide behind the nearly identical symbolism? We consider that to allow the students to progress in the adoption of abstract concepts it is necessary to provide activities that allow students to rationalize the organisation of conceptual knowledge, and so consolidate new learning. Classroom discussion based on activities of questioning or problem resolution, e.g. when electrolytes and the energetic aspects of chemical reactions are introduced, could make it possible for students to become aware of their alternative conceptions and so support the integration of new knowledge.

The present study suggests that, in the particular context of French classrooms, it is also important for students to have opportunities to explore and test the way ideas about conservation ("nothing is lost…"), and ideas about identify (the 'element' being present in compounds) are to be understood in chemical transformations. Teachers have to find ways to model the intended use of these abstract ideas, so that they are not just mottoes to be learnt by rote, but develop into meaningful understandings that can be operationalised in a way that supports and demonstrates developing understanding of the science.

The study reported here demonstrates the importance of exploring student learning in diverse educational contexts. Studies which explore learning difficulties (and successes) in relation to the details of specific curriculum and linguistic contexts can collectively inform the development of more effectively pedagogy in teaching the more challenging aspects of science.

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APPENDIX 1:
All questions are translations of the original French used in the questionnaire

Question 1: *How do you see the chemical transformation (or chemical reaction) with regards to the changes within atoms and molecules?*

a) During chemical transformation the nature of molecules is not changed,
☐ 1. fully in agreement ☐ 2. somewhat in agreement ☐ 3. somewhat in disagreement ☐ 4 fully in disagreement.
Justify your position:

b) During chemical transformation, the nature of atoms is not changed.
☐ 1. fully in agreement ☐ 2. somewhat in agreement ☐ 3. somewhat in disagreement ☐ 4 fully in disagreement.
Justify your position:

Question 2:

c) During chemical transformation, inter-molecular bonds (between molecules) are broken,
☐ 1. fully in agreement ☐ 2. somewhat in agreement ☐ 3. somewhat in disagreement ☐ 4 fully in disagreement.
Comment:

d)) During chemical transformation, intra-molecular bonds (between atoms within molecules) are broken,
☐ 1. fully in agreement ☐ 2. somewhat in agreement ☐ 3. somewhat in disagreement ☐ 4 fully in disagreement.
Comment:

Question 3:
When a piece of hot sodium metal is introduced in a gas jar of chlorine, a violent reaction takes place, and solid sodium chloride is formed.
How can the change from solid Na and gaseous Cl_2 to solid NaCl be explained?

Question 4:
Water is added to a gas jar of hydrogen chloride gas. Because of the contact with water the gas produces hydrochloric acid
How can the production of hydrochloric acid from hydrogen chloride and water be explained?